# Energy Efficient Routing and Self-Configuring Networks

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# Cornell Networking Effort – Fall 2001

- Quantifying performance improvement provided by directed diffusion (collaboration with Deborah Estrin).
- Enhancing performance of content-aware networking through more powerful aggregation techniques.
- Developing simulation testbed for experimental verification of the analytical and theoretical results in the above two areas.
- Continued focus on bounded complexity – managing problem difficulty in self-organizing sensor networks.

# Modeling Data-Centric Routing

- Optimal Aggregation: The optimum number of transmissions required per datum for a simple data-centric protocol is equal to the number of edges in the minimum Steiner tree - NP complete in general.
- Suboptimal Approaches:
  - Center at Nearest Source
  - Shortest Paths Tree
  - Greedy Incremental Tree
- Performance Measures:
  - Energy Savings
  - Delay
  - Robustness

# Energy Savings Due to Data Aggregation

- Theoretical Results: “The Impact of Data Aggregation in Wireless Sensor Networks” by Krishnamachari, Estrin, and Wicker
  - Gains with respect to address-centric clearly lie in aggregation
  - Even simple duplicate-suppression/max/min aggregation functions can provide significant gain.
    - Bounds derived for several cases
    - Experimental results support analysis
  - Source-sink placements and network topology impact performance and complexity of aggregation techniques.
  - Results suggest a tradeoff between energy and delay that could be incorporated into data-centric routing schemes.

# Energy Savings Due to Data Aggregation

- Let the fractional energy savings from using data aggregation be $\eta = N_D/N_A$.

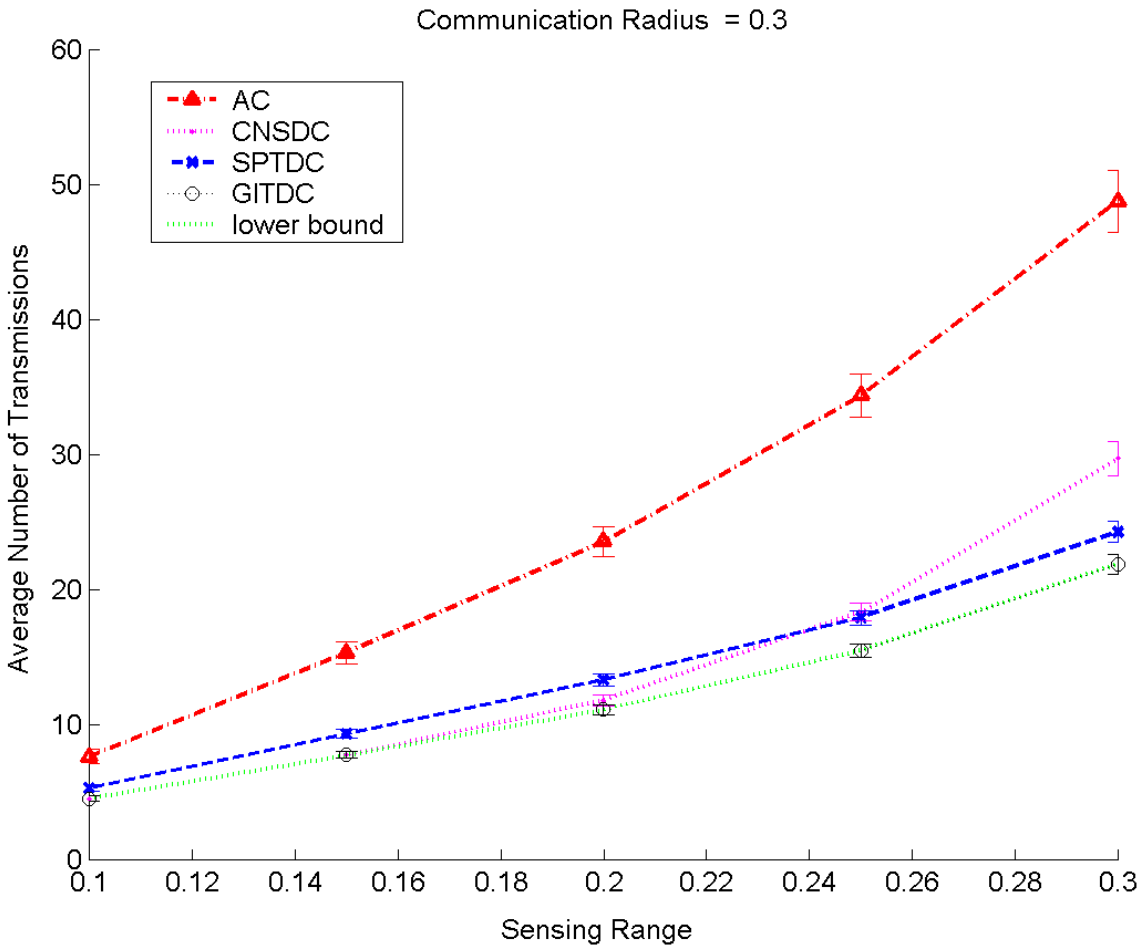
- If we have k sources, $i^{th}$ source at distance $d_i$ hops from sink, and diameter X for the sources:

$$((k-1)X+\min(d_i))/\Sigma d_i \leq \eta \leq (\min(d_i) + k - 1)/\Sigma d_i$$

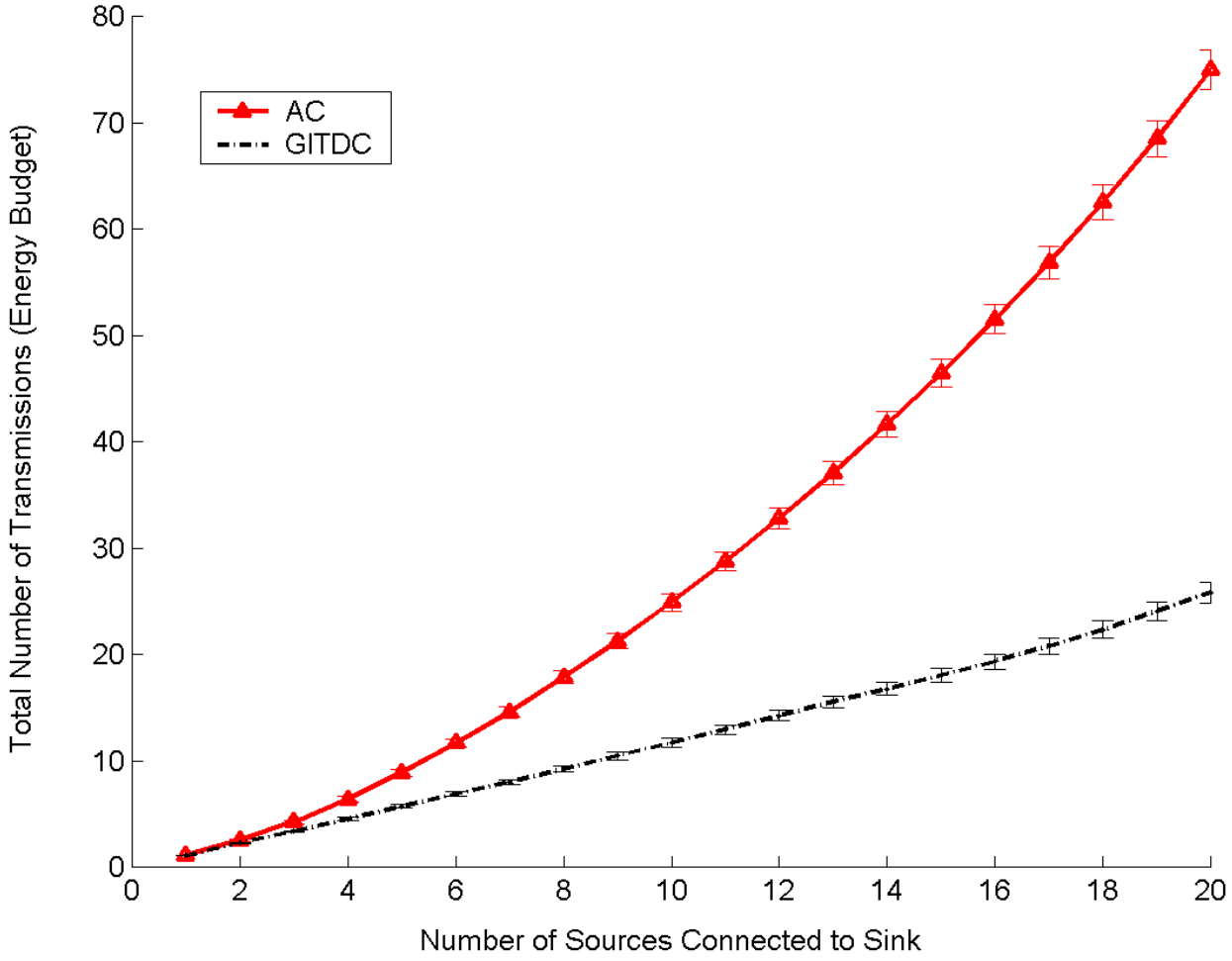
$$\lim_{d\to\infty} \eta = 1/k$$

- If the subgraph induced by the set of sources is connected, then the optimal aggregation tree can be formed in polynomial time.

# Energy Savings Due to Data Aggregation



# Robustness with Data-Aggregation



# Advanced Aggregation Techniques

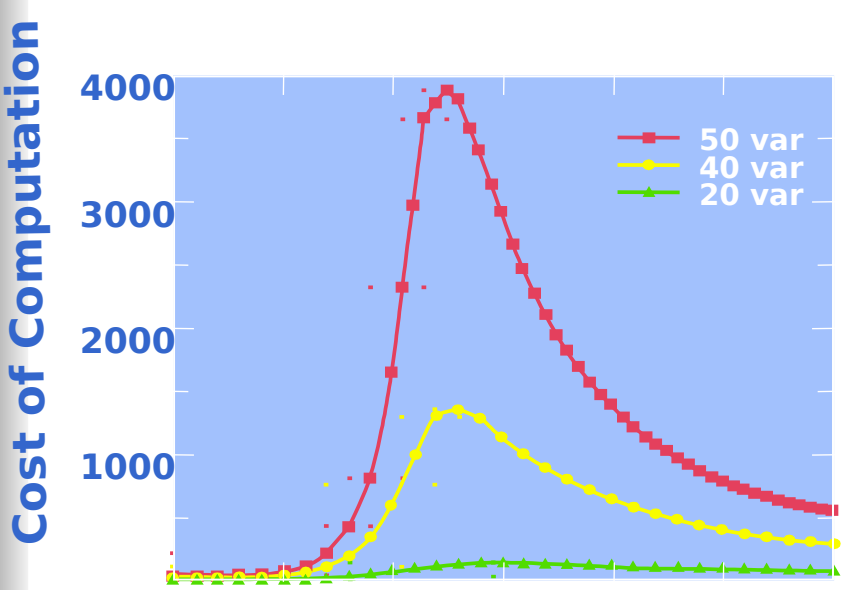
- Interests can be expressions in first order logic – interest now takes the form of question: Is this true about the world/battlefield/area?
- Individual terms in conjunctive normal form now become focus for aggregation.
  - Pushes computation further out into network
  - Naturally balances computation load in energy-limited sensor network
- Interests can also be expressed as continuous-valued random variables.
  - Aggregation performed through belief propagation
  - Minimizes number of transmissions required to update local marginal distributions.

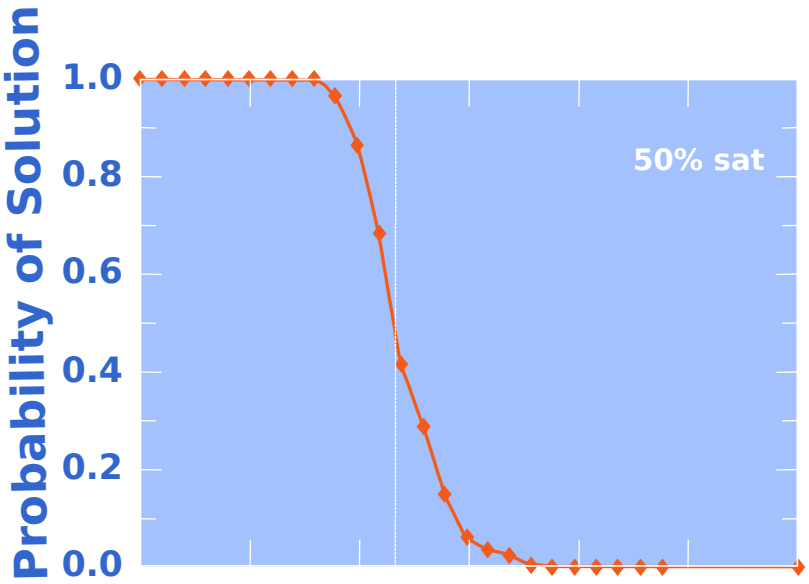
# Simulation Testbed and Future Effort

- OPNET simulation testbed for directed diffusion completed for case of static nodes.
- Future emphasis on modeling mobility.
- Analytic and simulation results from new interest definitions to be presented at the next PI meeting.

# Bounded Complexity

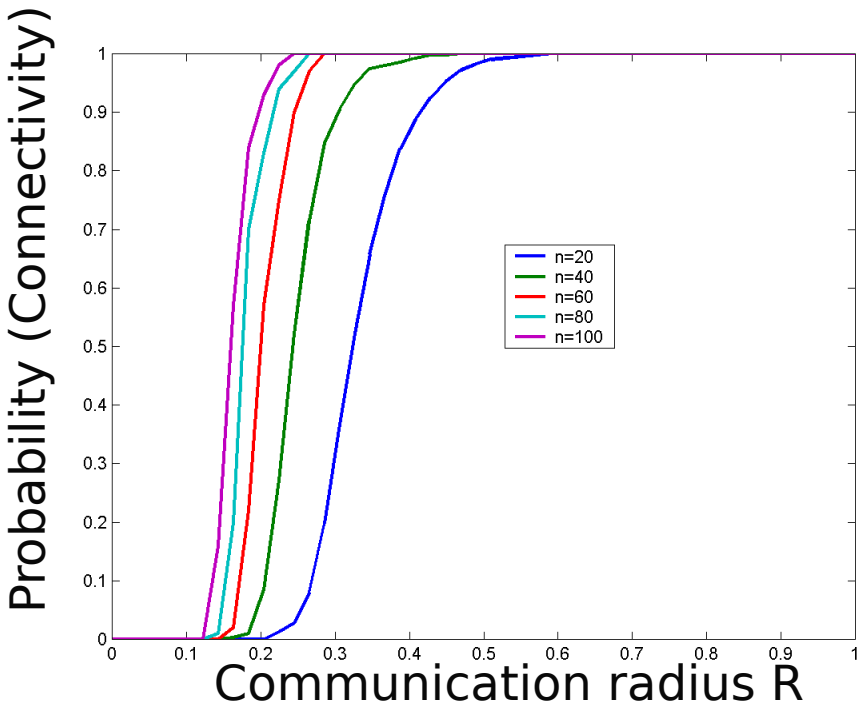
- Critical density thresholds found for many wireless network properties and for distributed constraint satisfaction problems.
  - “Phase Transitions in Wireless Networks” - Krishnamachari, Wicker and Bejar (GlobeCom’01)
  - “Distributed Problem Solving and the Boundaries of Self-Configuration in Wireless Networks” - Krishnamachari, Bejar, and Wicker (HICSS ‘02)



# Phase Transition for Connectivity

- Random Graph Model: n nodes randomly located in a unit area, varying communication range R.
- Density ~ $\pi R^2 n$.
- Connectivity threshold function with O(log n) density, proved by Gupta & Kumar (1998).

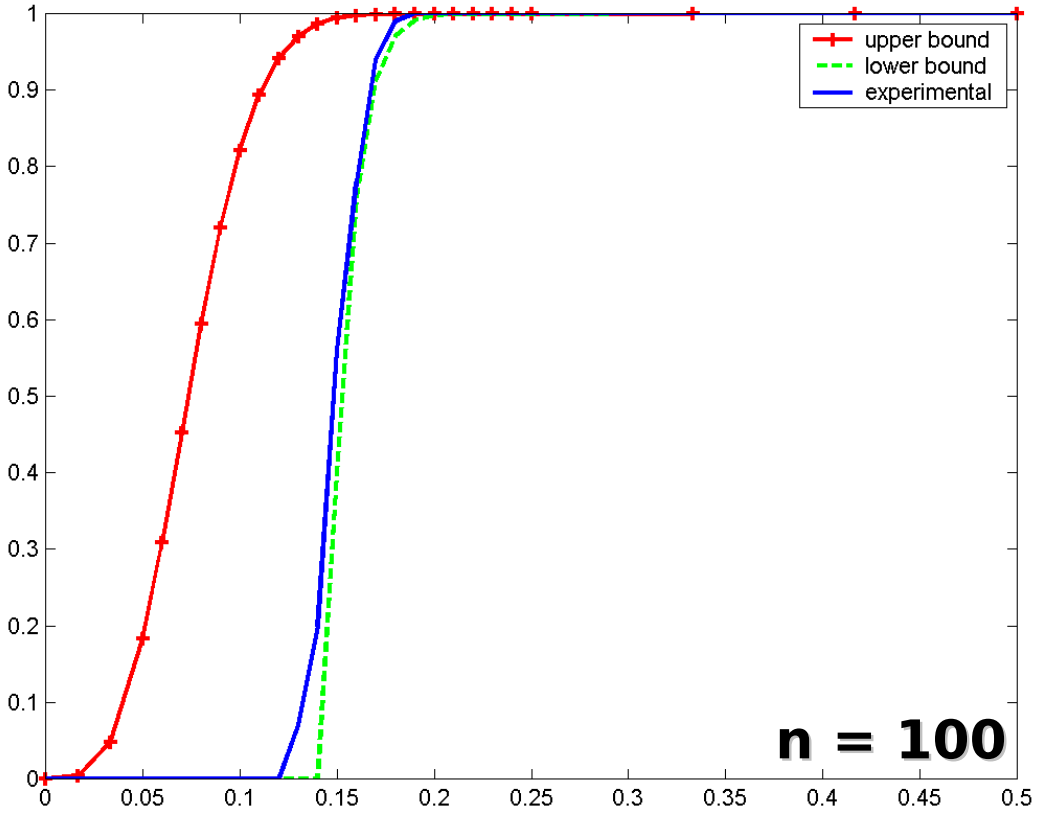


# Analytical results on phase transitions

- Transition effects on Bernoulli random graphs well studied analytically by mathematicians.
- Fixed-radius random graphs that model wireless networks do not have the same independence properties - making analysis much harder.
- Finding bounds is somewhat easier.

# Phase Transition Bounds

- Probability that all nodes have at least 2 neighbors




Communication radius R

# Analytical Bounds for Neighbor Count

- Property: All nodes have at least k neighbors
- Let $A_i$ = event that node i has at least k neighbors.
- Bounds:

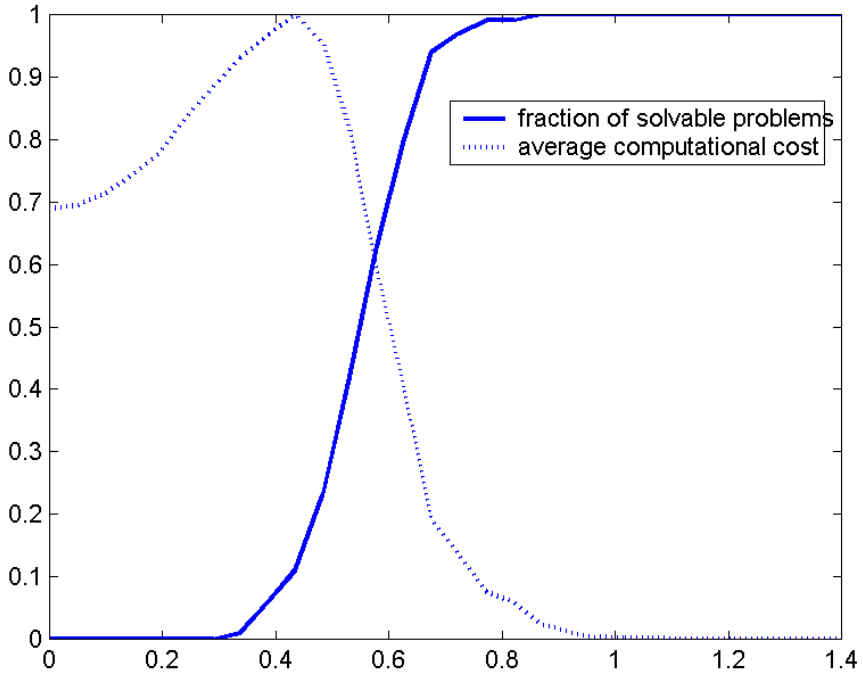
$$1 - Pr(A_i^c) \geq Pr(\bigcap_{i=1}^{n} A_i) \geq 1 - nPr(A_i^c)$$

where (for $R \leq 0.5$, ignoring edge effects)

$$Pr(A_i^c) = \sum_{j=0}^{k-1} \binom{n-1}{j} (\pi R^2)^j (1 - \pi R^2)^{n-1-j}$$

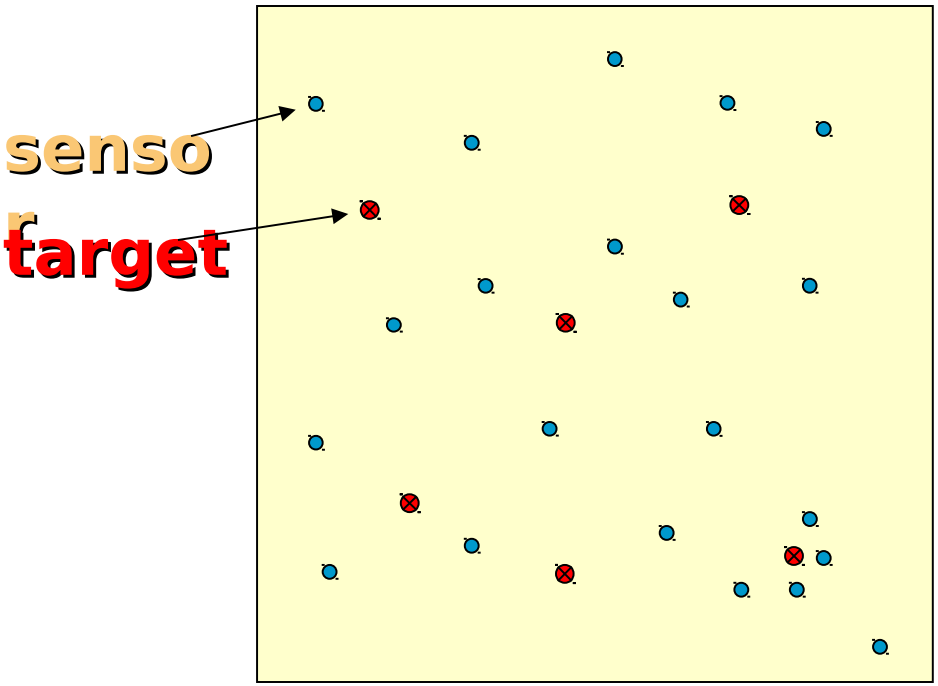
# Hamiltonian Cycle Formation

- A self-configuration task useful as precursor to many efficient distributed algorithms
- NP-complete in the worst case, but easy on average beyond O(n log n) critical density threshold.



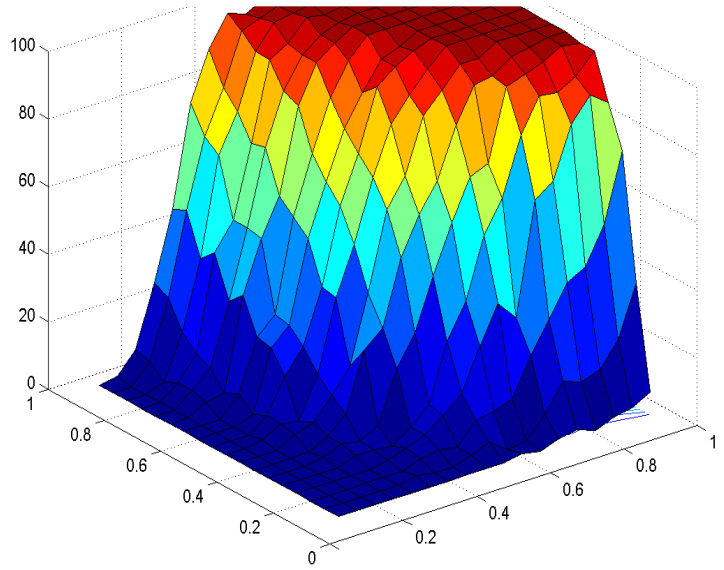
# Coordinated Sensor Tracking

- Multiple sensors and targets
- Sensors communicate and sense locally
- Need 3 communicating sensors to track each target



# Coordinated Sensor Tracking

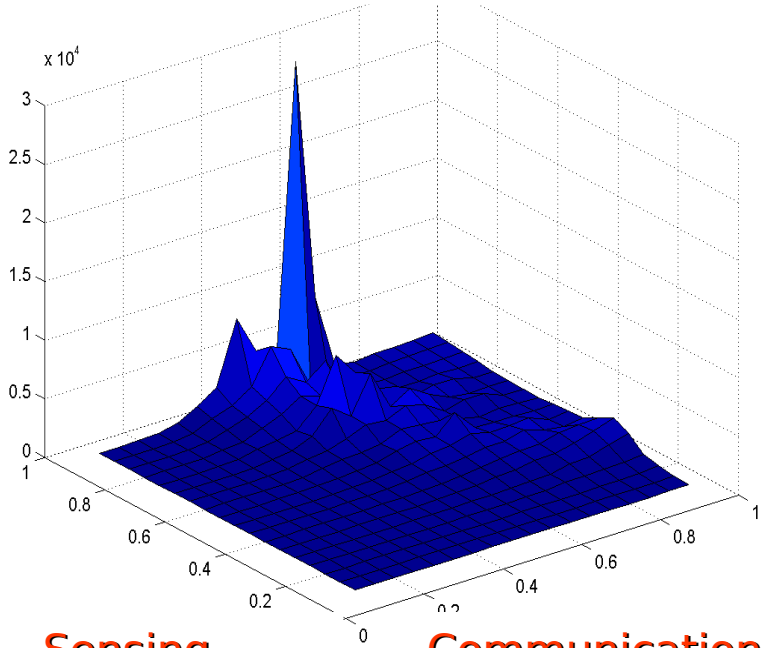
## Probability of Tracking




Sensing Range

Communication Range

## Mean Computation Cost

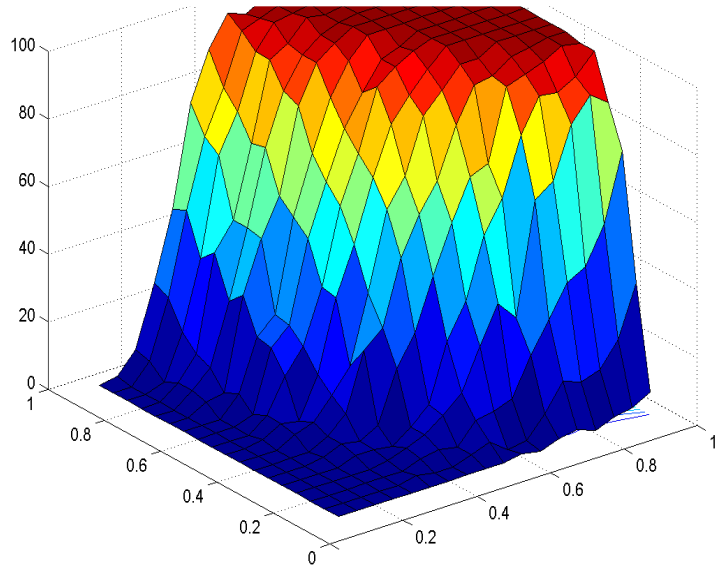



Sensing Range

Communication Range

# Coordinated Sensor Tracking

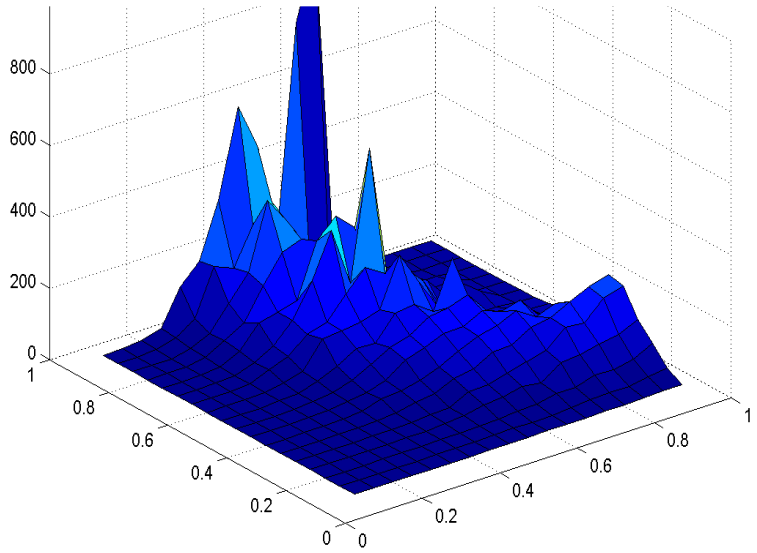
## Probability of Tracking




Sensing Range

Communication Range

## Mean Communication Cost




Sensing Range

Communication Range

# Usefulness of Phase Transition Perspective

- Helps determine range of feasible densities for various network properties
- Can be computed offline or incorporated into online self-configuration mechanisms.
- Helps bound the computational/communication complexity of distributed algorithms.

End